



Rehabilitation of a Shallow Lake (Big Muskego Lake, Wisconsin) Via Drawdown: Sediment Response

by William F. James, Harry L. Eakin, and John W. Barko

PURPOSE: This technical note examines changes in sediment physical and chemical characteristics as a result of drawdown and refill of shallow Big Muskego Lake (Wisconsin) to promote macrophyte growth. Information obtained from this study may be used to assess positive (i.e., sediment consolidation) and negative (i.e., sediment nutrient release) impacts of drawdown on sediment dynamics and the potential for macrophyte growth in shallow lake rehabilitation programs.

BACKGROUND: The positive roles played by submersed aquatic macrophytes in reducing sediment resuspension in shallow lakes and reservoirs may often be disturbed by high external nutrient loadings and turbidity, unexpected lake level fluctuations, explosions of benthic fish communities, and/or other ecosystem-level stresses such as strong storms or high winds, resulting in macrophyte community instability and a changeover to a more turbid, algal-dominated state with loss of macrophyte dominance (Scheffer 1990; Scheffer et al. 1993). One of the goals of shallow lake rehabilitation, therefore, is the reestablishment and maintenance of stable submersed macrophyte communities for purposes of reducing sediment resuspension, sediment export, and improving water quality (Scheffer et al. 1994). Scheffer (1998) describes several restoration techniques for improving the shallow aquatic environment for macrophyte growth. After favorable water quality conditions are established (i.e., watershed nutrient loading reduction, depletion of benthic fish stock, and other biomanipulations), one technique available for inducing macrophyte growth in shallow, algal-dominated systems is a lake drawdown (Scheffer 1998). Desiccation of sediments for purposes of consolidation can temporarily arrest resuspension potential and reduce turbidity after lake refill, thereby promoting greater light penetration for macrophyte growth (Scheffer 1998). Lake drawdown can also be used to concentrate and remove undesirable fish populations that promote high levels of turbidity.

In contrast to the positive benefits a lake drawdown can have on the water quality of shallow lakes, sediment desiccation may result in some undesirable impacts such as enhanced rates of nutrient release from sediments after refill (Fabre 1988), particularly if organic sediment nitrogen (N) and phosphorus (P) pools are mobilized during desiccation and oxidation. The outcome of enhanced rates of internal nutrient loading from consolidated sediments could be the development of a large pulse of N and P to the water column and stimulation of excessive algal growth, which would compete for available light. Information is needed regarding the impacts of sediment desiccation on nutrient mobilization in order to better evaluate management alternatives for promoting macrophyte growth in shallow aquatic systems.

The objectives of this research were to evaluate changes in sediment physical and chemical composition and internal phosphorus loadings in Big Muskego Lake as a result of a lake drawdown and refill to promote submersed and emergent macrophyte growth. Here, we report results of information collected in 1995, prior to drawdown (1996), during drawdown (1997), immediately

DISTRIBUTION STATEMENT A

Approved for Public Release
Distribution Unlimited

after lake refill, and 1 year after lake refill (1998). Studies by others regarding changes in macrophyte biomass and assemblage and water quality will be reported at a later date.

STUDY SITE: Big Muskego Lake (Figure 1), located in east-central Wisconsin, is very shallow with a mean depth of only 0.75 m. It has a surface area of 840 ha and drains a predominantly agricultural watershed (7,600 ha). Tributary inflows include drainage from Little Muskego Lake (not shown) and a deeper (10-m) glacial lake, Bass Bay. Big Muskego Lake discharges into another glacial lake, Wind Lake. The lake has been eutrophic in recent decades, with a summer trophic state index value for total phosphorus concentration (>50 mg/L) exceeding 60 units before lake drawdown (Carlson 1977). It has exhibited a submersed plant community dominated by *Myriophyllum spicatum* and a fishery dominated by *Cyprinus carpio* (L.). In 1995, Big Muskego Lake was subjected to a biomanipulation to remove benthic-feeding carp and a lake drawdown to consolidate sediments and stimulate submersed macrophyte growth.

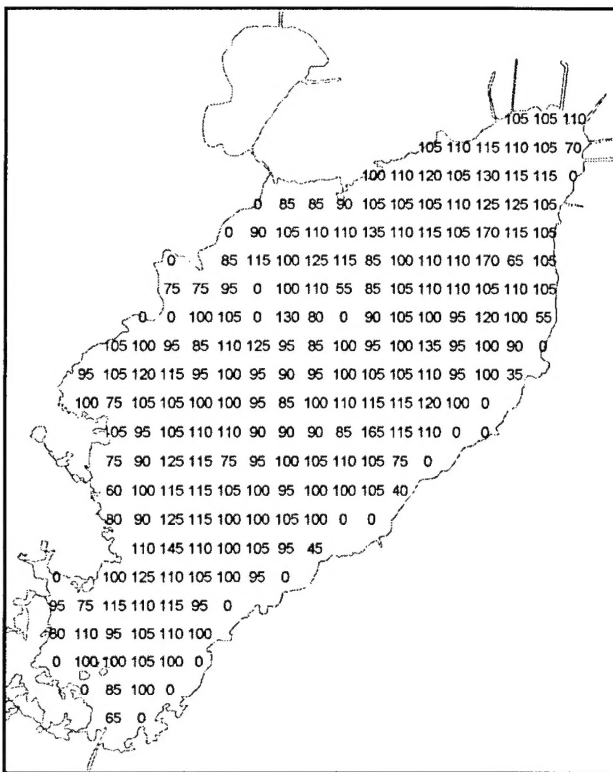


Figure 1. Bathymetry of Big Muskego Lake

METHODS: During August 1995, August 1996, July 1997, and August 1998, sampling stations were established in Big Muskego Lake ($n=54$) for examination of changes in sediment characteristics and laboratory rates of nutrient release from sediments before, during, and after lake drawdown (Figure 2). For each year, sampling stations were selected randomly from an array of Universal Transverse Mercator (UTM) coordinates established at 200-m intervals throughout the lake. Sampling stations were located by a global positioning system (GPS).

Sediment samples were collected at each station with a Wildco KB sediment core sampler (Wildlife Supply Co., Saginaw, MI). The upper 10 cm of sediment were immediately extruded into an airtight container to preserve the redox integrity of the sample. In the laboratory, sediments were gently homogenized under a nitrogen atmosphere prior to fractionation. Fresh sediment was carefully placed in a crucible and dried at 105°C to a constant weight for determination of moisture content and sediment density (Allen et al. 1974), then combusted at 550°C in a muffle furnace for determination of particulate organic matter (POM). Care was taken to minimize compaction of sediment in the crucible for density determination. Additional sediment was centrifuged at 4°C at 3000 rpm for approximately 2 hr for separation of sediment porewater. The porewater was carefully decanted under a nitrogen atmosphere, filtered through a $0.45\text{-}\mu\text{m}$ filter (Gelman GN-6 Metricel), and analyzed for soluble reactive P (SRP) and ammonium-nitrogen ($\text{NH}_4\text{-N}$) using methods described in American Public Health Association (1992). Total sediment N and P concentrations

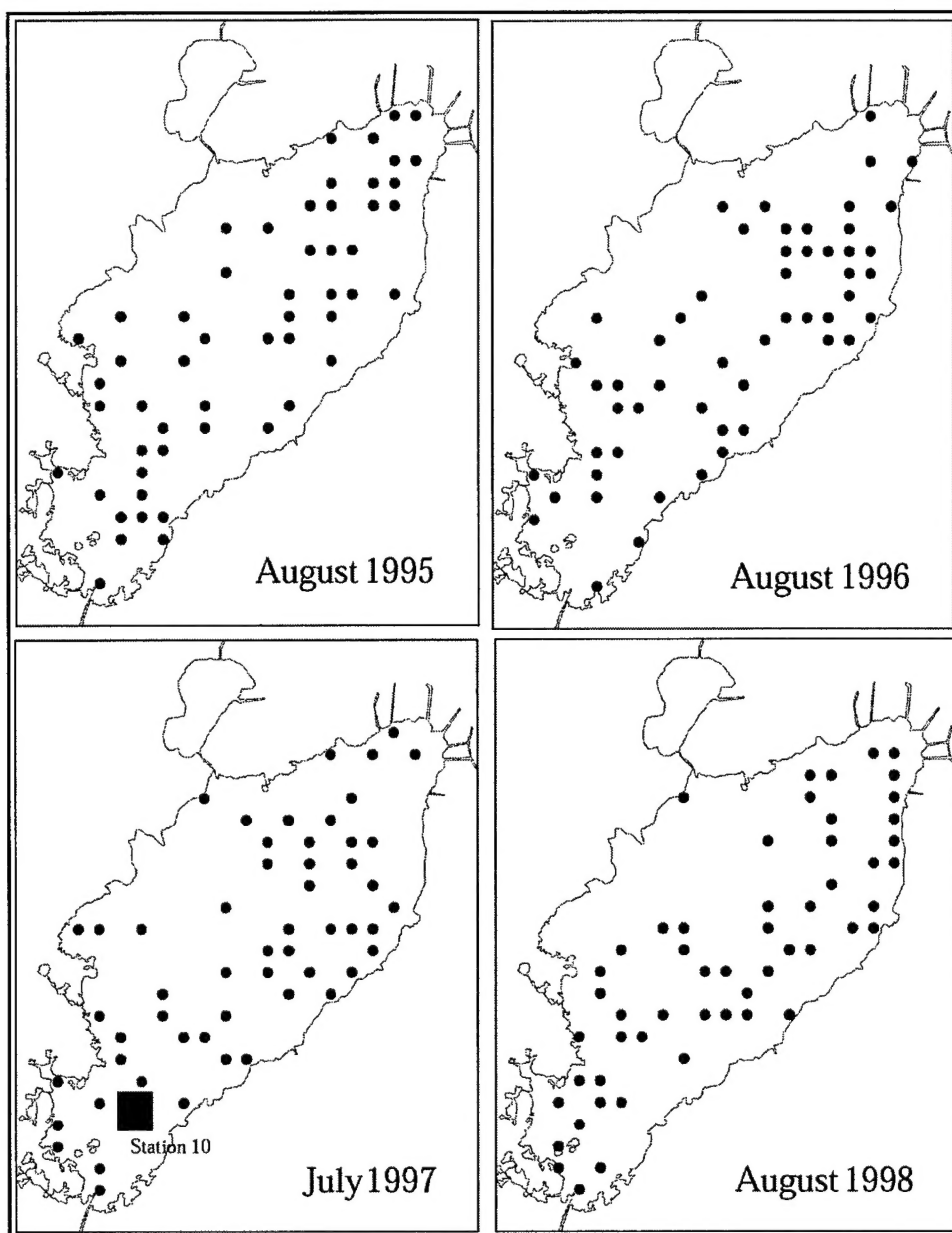


Figure 2. Sediment sampling locations in 1995-98. The black square (Station 10) in 1997 represents pH monitoring station

were analyzed colorimetrically using Lachat QuikChem procedures (Lachat Method 10-107-06-2-D for nitrogen and 13-115-06-1-B for phosphorus; Zellweger Analytics, Lachat Div., Milwaukee, WI) following digestion with sulfuric acid, potassium sulfate, and red mercuric oxide (Plumb 1981). Sequential fractionation of inorganic phosphorus in the sediment was conducted according to Hieltjes and Lijklema (1980) for the determination of NH_4Cl -extractable phosphorus (NH_4Cl -P; loosely bound and CaCO_3 -adsorbed phosphorus), NaOH -extractable phosphorus (NaOH -P; aluminum- and iron-bound phosphorus), and HCl -extractable phosphorus (HCl -P; calcium-bound phosphorus). Each extraction was filtered through a $0.45\text{-}\mu\text{m}$ filter, adjusted to pH 7, and analyzed for SRP. Sediment concentrations are expressed in units of mg g^{-1} dry sediment mass.

From a subset of sediment sampling stations (n=18), sediment cores (6.5-cm ID and 50-cm length) were collected for laboratory incubation under oxic and anoxic conditions during each sampling year. The core liners, containing both sediment and overlying water, were sealed immediately using stoppers and stored in a protective box until analysis. Additional lake water was collected for incubation with the collected sediment.

In the laboratory, rates of P release from sediments under oxic and anoxic conditions were evaluated in incubation systems according to the procedures described in James and Barko (1991) and James, Barko, and Eakin (1995). Incubation systems were constructed by extruding the upper 10-cm section of sediment into a core liner (6.5-cm ID and 25-cm length), siphoning 300 ml of filtered (Gelman A/E glass fiber) lake water onto the sediment, and sealing the system with rubber stoppers. The redox environment in each system was controlled by bubbling the water with air (for oxic conditions) or nitrogen (for anoxic conditions). Sediment systems were incubated at 20 °C over a 2-3 week period to simulate in situ temperatures during summer. Samples were collected in the middle of the water column in each system on a daily basis for SRP analysis. Rates of P release from the sediment ($\text{mg m}^{-2} \text{d}^{-1}$) were calculated as the linear change in concentration in the overlying water divided by time and the area of the incubation core liner.

In 1997 (shortly after lake refill), nine additional sediment cores were collected from a station located in the southwestern region of the lake (Station 10; Figure 2) to examine the effects of elevated pH on P release from sediments under oxic conditions. The pH levels in these oxic systems were adjusted to approximately 9.3 by bubbling the systems with CO₂-free air (Boers 1991).

pH was measured in situ in Big Muskego Lake every hour at station 10 (Figure 2) from July through September 1997 using a recording YSI 6000 (Yellow Springs Instruments, Yellow Springs, OH). The probe was positioned about 20 cm above the sediment interface by securing the sonde unit to a platform permanently anchored into the sediments. At biweekly intervals, the sonde unit was removed from the water column for data retrieval and servicing. At those times, the pH probe was cleaned gently with distilled water and calibrated against known buffers before redeployment.

RESULTS: Drawdown of Big Muskego Lake was initiated in October 1995 (Figure 3). The lake was lowered approximately 0.5 m below normal pool elevation between December 1995 and July 1996. In mid-July 1996, a channel was excavated to promote further drawdown. Thereafter, the lake elevation declined an additional 0.5-0.6 m between July 1996 and January 1997. The lake was allowed to refill during late winter and early spring 1997. Normal pool elevation was achieved by April 1997. During the entire drawdown period, rains caused temporary increases in pool elevation and inundation of sediments. In particular, periodic spikes in measured pool elevation as a result of storms were observed during April through July 1996, when the pool elevation was maintained at 0.5 m below the dam crest (Figure 3). Overall, approximately 13 percent of the sediment area was exposed for approximately 1 year, while over 80 percent of the sediment area was exposed for a period of approximately 6 months.

Since most of the sediment area in Big Muskego Lake was exposed for at least 6 months, all data collected for each year were pooled. Overall, mean moisture content of the surface sediments in Big Muskego Lake was very high (more than 90 percent) while mean sediment density was low in 1995 (Figure 4), reflecting the fluid nature of the sediment before lake drawdown. Mean organic matter

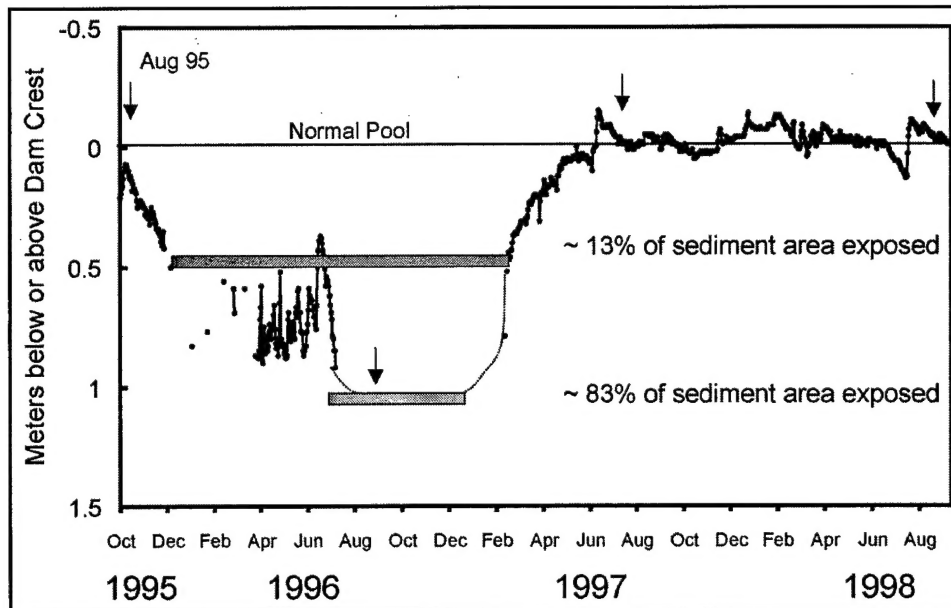


Figure 3. Variations in pool elevation for Big Muskego Lake between 1995 and 1998. The dotted line between July 1996 and February 1997 represents estimated elevation based on visual observation. The actual pool elevation declined below the staff gauge during this period. Thick horizontal lines represent length of time that approximately 13 and 83 percent of the lake sediments were exposed to air. Arrows represent sediment sampling dates

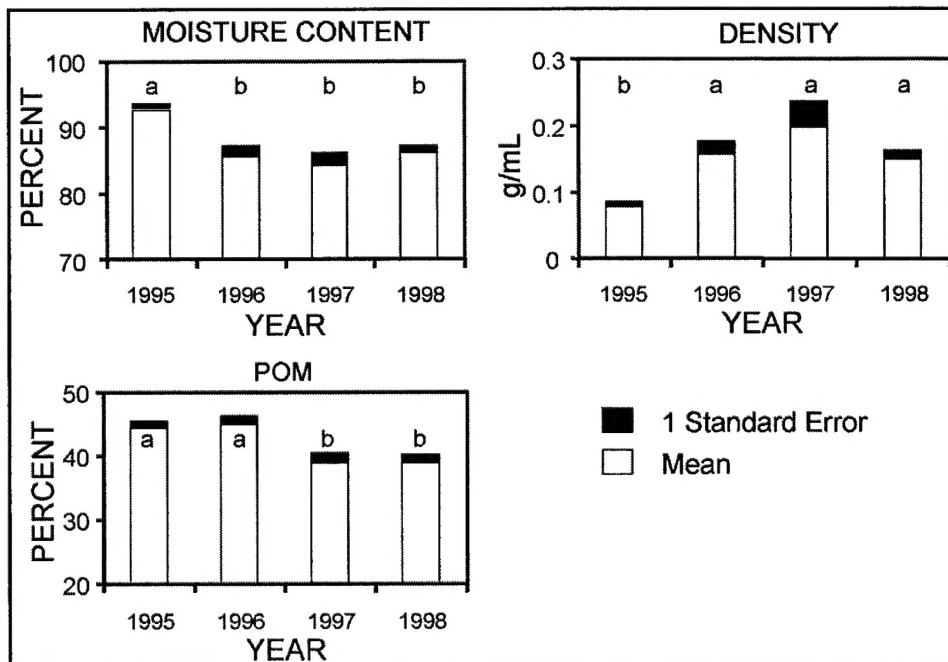


Figure 4. Means ($n = 50-54$; white column) and one standard error (black column) for sediment moisture content, sediment density, and particulate organic matter as a function of year. Letters indicate significant differences at the 5-percent level or less based on Duncan's Multiple Range Analysis (Statistical Analysis System 1994)

content of the sediments was also very high in the lake (more than 40 percent) before drawdown (Figure 4). The mean organic matter content declined significantly after lake refill in 1997 and 1998 relative to the mean observed in 1995 ($p < 0.05$; Analysis of Variance (ANOVA); Statistical Analysis System 1994), suggesting some oxidation of a portion of the sediment organic matter. Both during lake drawdown (i.e., 1996) and shortly after refill (i.e., 1997), sediment moisture content decreased significantly ($p < 0.05$; ANOVA), while sediment density increased significantly ($p < 0.05$) over means observed in 1995, indicating consolidation of sediment. One year after refill (i.e., 1998), mean sediment moisture content increased slightly while mean sediment density declined over values observed in 1997. These changes were not, however, statistically different from means observed in 1996 and 1997.

In 1995, mean concentrations of SRP in the porewater of the sediment were very low (Figure 5). Mean porewater P in 1996 and 1997 increased significantly ($p < 0.05$; ANOVA) over 1995 levels by an order of magnitude as a result of lake drawdown and subsequent refill. One year after lake refill (1998), mean porewater P declined markedly compared to means observed in 1996 and 1997, and was not statistically distinguishable from the mean observed in 1995. Mean porewater $\text{NH}_4\text{-N}$ also increased significantly in 1996 ($p < 0.05$; ANOVA), relative to pre-drawdown levels in 1995 (Figure 5). Mean porewater $\text{NH}_4\text{-N}$ concentrations declined in 1997 and 1998 and were not statistically different from the mean observed in 1995.

In contrast to $\text{NH}_4\text{-N}$ and SRP concentration patterns in the porewater, mean sediment total P declined significantly ($p < 0.05$; ANOVA) in the upper 10-cm sediment layer during lake drawdown and refill (i.e., 1997-98; Figure 6). Associated with this decline were significant ($p < 0.05$; ANOVA) decreases in the concentration of organic P, $\text{NH}_4\text{Cl-P}$, and NaOH-P in 1997-98 (Figure 7). In contrast, the more refractory HCl-P fraction did not change as a result of drawdown and refill.

Mean total sediment N in Big Muskego Lake was very high prior to lake drawdown (Figure 6), compared to the range of values for different sediments reported in Barko and Smart (1986), but did not change significantly as a result of lake drawdown and refill. As a result of these patterns, the sediment N:P ratio

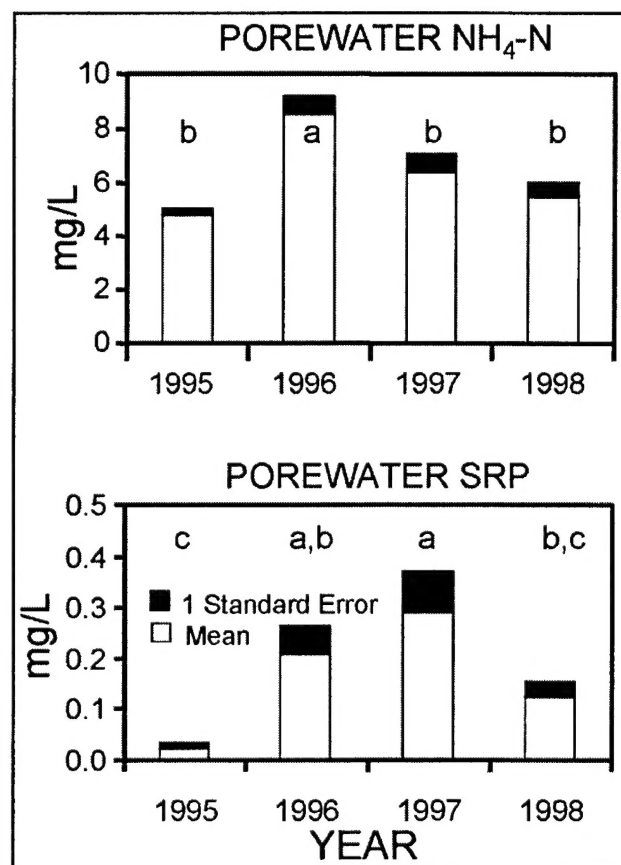


Figure 5. Means ($n = 50\text{-}54$; white column) and one standard error (black column) for sediment pore water ammonium-nitrogen ($\text{NH}_4\text{-N}$) and phosphorus (SRP) as a function of year. Letters indicate significant differences at the 5-percent level or less based on Duncan's Multiple Range Analysis (Statistical Analysis System 1994)

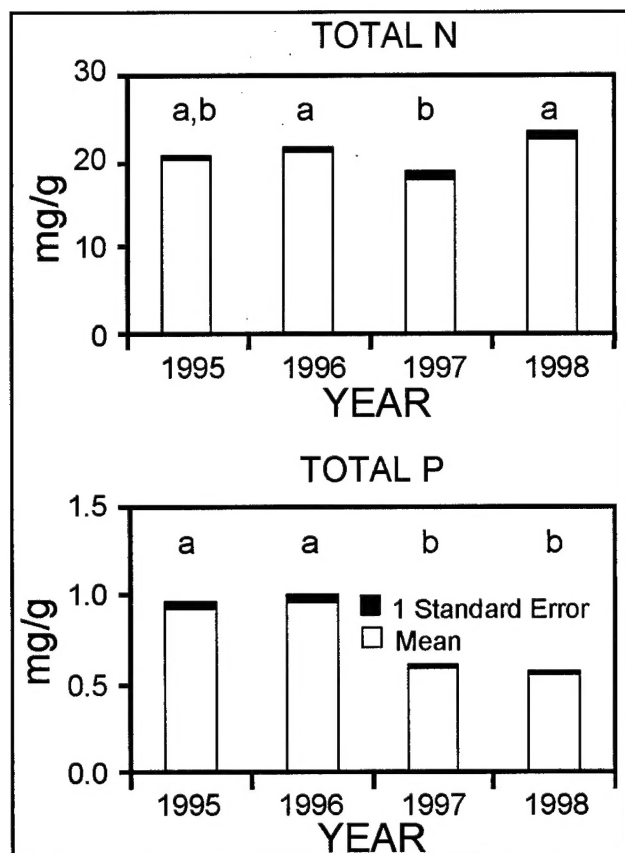


Figure 6. Means ($n = 50-54$; white column) and one standard error (black column) for sediment total nitrogen (N) and total phosphorus (P) as a function of year. Letters indicate significant differences at the 5-percent level or less based on Duncan's Multiple Range Analysis (Statistical Analysis System 1994)

shifted from approximately 20 in 1995 to approximately 40 in 1998.

Organic matter and nutrient concentrations in the sediment were normalized with respect to the original sediment mass in the upper 10 cm before drawdown in 1995 to account for compaction as a result of sediment dewatering (Table 1). Sediment organic matter, total sediment P, $\text{NH}_4\text{Cl-P}$, NaOH-P , and the organic sediment P fractions exhibited a trend of decreasing mass as a result of drawdown and refill. Sediment total N mass fluctuated around a grand mean of 160 g/m^2 over all years with no apparent net change between 1995 and 1998.

Laboratory rates of P release from sediments, measured at 20°C under both oxic and anoxic conditions, were very low (near zero) in Big Muskego Lake prior to drawdown in 1995 (Figure 8). Lake drawdown and sediment exposure in 1996 were accompanied by a slight increase in the mean rate of P release from sediments under oxic conditions, while refill of the lake in 1997 coincided with a marked increase in the mean rate of P release from sediments under both oxic and anoxic conditions. In 1998, one year after refill, the mean rate of P release from sediments declined significantly over means observed in 1997 (Figure 8).

Following lake refill and the establishment of dense stands of submersed and emergent macrophytes in 1997 (see "Discussion"), mean daily pH was very high throughout the summer (exceeding 9.5 pH units) at station 10 in Big Muskego Lake (Figure 9). Elevated pH did not appear to enhance laboratory rates of P release for sediments collected near station 10 in Big Muskego Lake (Table 2). Although rates of P release increased slightly as a function of pH, rates were not significantly different at pH values of approximately 8.5 and approximately 9.3.

DISCUSSION: A prominent feature of Big Muskego Lake was the very high moisture content, low sediment density, and high organic matter content of the surficial sediments. Lake drawdown was effective in consolidating the sediment (i.e., increasing sediment density) and causing a decrease in organic matter content. These responses in sediment texture and organic matter content are of importance in shallow lake rehabilitation efforts to stimulate macrophyte growth, as Barko and Smart (1986) indicated that changes in these sediment characteristics can directly influence growth

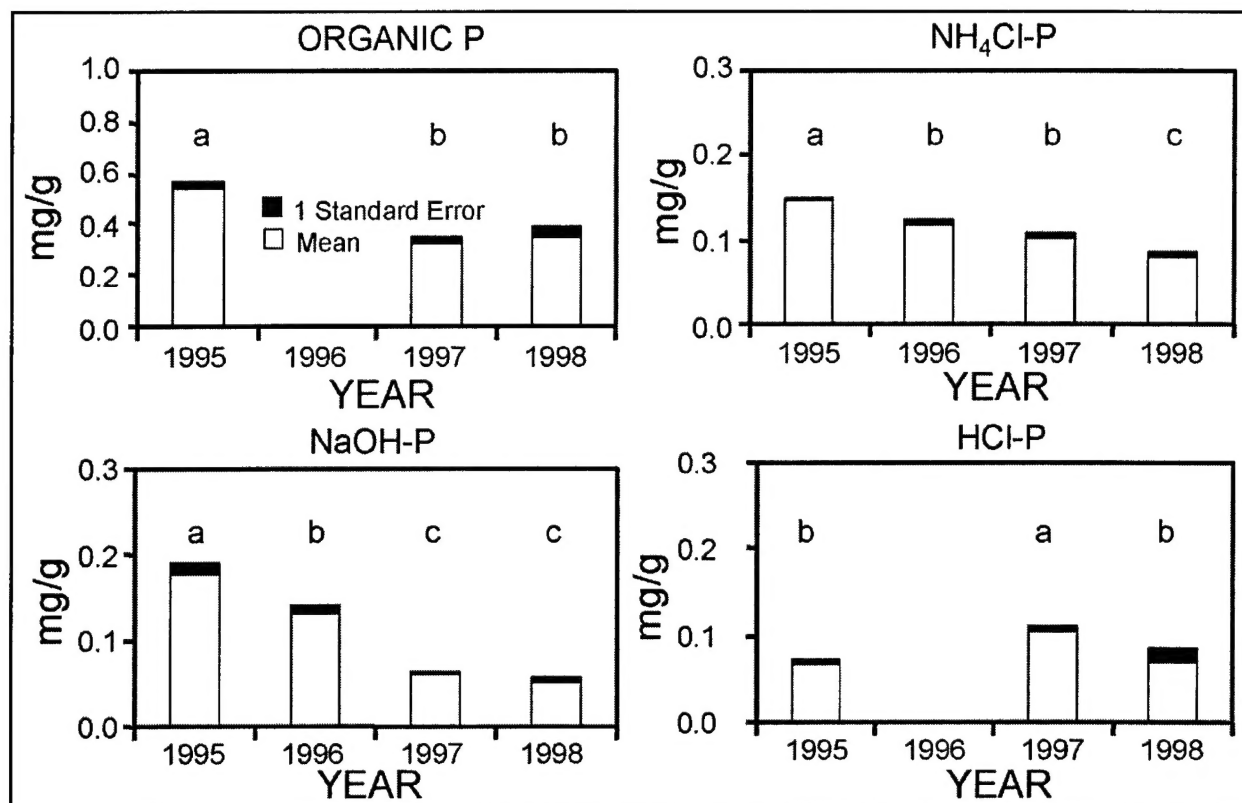


Figure 7. Means (n = 50-54; white column) and one standard error (black column) for sediment organic phosphorus (P), NH₄Cl-extractable P (NH₄Cl-P), NaOH-extractable P (NaOH-P), and HCl-extractable P (HCl-P) as a function of year. Letters indicate significant differences at the 5-percent level or less based on Duncan's Multiple Range Analysis (Statistical Analysis System 1994)

Table 1
Changes in NH₄Cl-P, NaOH-P, HCl-P, Organic Phosphorus, Total Phosphorus, and Total Nitrogen in the Sediment¹

Year	Compacted sediment depth (cm)	Particulate Organic Matter (kg/m ²)	NH ₄ Cl-P (g/m ²)	NaOH-P (g/m ²)	Hcl-P (g/m ²)	Organic-P (g/m ²)	Total Sediment P (g/m ²)	Total Sediment N (g/m ²)
1995	10	3.45	1.14	1.39	0.53	4.21	7.28	157.9
1996	4.9	3.5	0.93	1.03	N.D.	N.D.	7.60	165.4
1997	3.9	3.0	0.81	0.47	0.82	2.56	4.64	141.8
1998	5.2	3.0	0.61	0.41	0.54	2.77	4.34	145.2

¹Areal mass was normalized with respect to the original sediment mass in the upper 10 cm before drawdown in 1995 to account for compaction as a result of sediment dewatering.

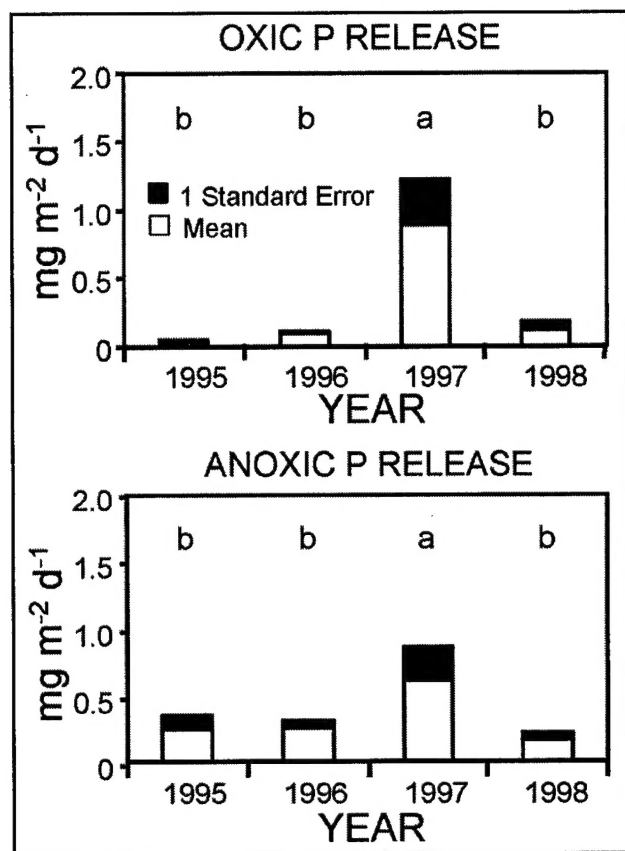


Figure 8. Means ($n = 50-54$; white column) and one standard error (black column) for laboratory rates of phosphorus release from sediments under oxic and anoxic conditions as a function of year. Rates were determined at 20 °C. Letters indicate significant differences at the 5-percent level or less based on Duncan's Multiple Range Analysis

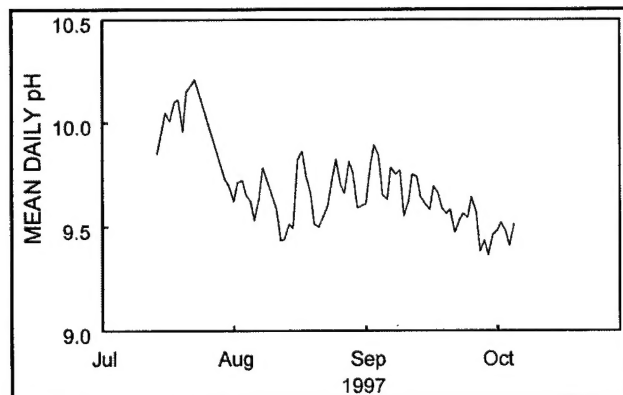


Figure 9. Mean daily pH at station 10 (see Figure 1 for station location) in 1997

potential. In particular, they demonstrated that macrophyte growth can be suppressed as a function of low sediment density and high organic content in laboratory experiments. Conversely, higher density sediments with lower organic matter content were associated with a higher macrophyte growth response in their experiments. Sediment consolidation can also result in improved growth potential via greater light penetration by increasing the critical shear stress required to resuspend sediment (Mehta et al. 1982).

Drawdown and refill of Big Muskego Lake were associated with the occurrence of significant increases in concentrations of pore water $\text{NH}_4\text{-N}$ and SRP and rates of P release under both oxic and anoxic conditions. In contrast, concentrations of $\text{NH}_4\text{-N}$ and SRP in the pore water and rates of P release from the sediments under oxic and anoxic conditions were minimal before lake drawdown. Others have shown temporary increases in pore water $\text{NH}_4\text{-N}$ and SRP of sediments after temporary desiccation and rewetting (De Groot and Van Wijck 1993a). Although mechanisms causing these changes are not precisely known, increases in these sediment characteristics may be due to mineralization of organic N and P in the sediments during desiccation and oxidation and shifts in P equilibrium from solid to aqueous phases during lake refill. De Groot and Van Wijck (1993a, 1993b) and Fabre (1992) found that the iron-bound P fraction of the surface marsh sediment increased as a result of desiccation, suggesting oxidation of iron and sorption of P onto sediment particles. The sorption capacity of sediment for P also increased as a result of desiccation in their study. Rewetting of sediments after desiccation may drive P equilibrium toward P desorption, resulting in increases in pore water P.

Declines in total sediment P as a result of drawdown and refill could not be accounted for by elevated P release and net increases in pore

Table 2
Changes in the Rate of Phosphorus Release from Sediments in Big Muskego Lake Under Oxidic Conditions as a Function of pH¹

Treatment	pH	Mean Rate mg m ⁻² d ⁻¹	1 Standard Error
Control	8.5	3.6 ^a	1.1
CO ₂ -Free	9.3	4.7 ^a	1.1

¹Sediments were collected in the vicinity of Station 10. Control treatments were maintained at pH ~8.5 by purging the water column with air. CO₂-free treatments were maintained at a pH of ~9.3 via purging the water column with CO₂-free air. The letters next to the mean value indicate significant differences at the 5-percent level or less based on Duncan's Multiple Range Analysis (Statistical Analysis System 1994).

water SRP concentration. Net concentration and mass declines of total P in surface sediments may be due to high net flux of P from the sediment into the water and discharge from the system during initial refill in February through May of 1997, which was not examined. Fabre (1988) observed a pulse of P from sediments after refilling in a reservoir, which was attributed to elevated pH and resuspension as a result of refill.

Another mechanism of net P removal from the surface sediments may be root uptake by macrophytes and periphyton. Primarily emergent and submersed macrophytes, densely covering much of the lake during both 1997 and 1998 (150 g/m² in 1995 versus 1400 g/m² in 1998)¹ may have played a role in depleting sediment P reserves. The more labile NH₄Cl-P and NaOH-P fractions may become directly available for root uptake via redox reactions and equilibrium processes. Barko et al. (1988) demonstrated that macrophytes can substantially deplete extractable inorganic P fractions in the sediment for growth. Mobilization of sediment organic P fractions to inorganic forms via bacterial degradation can also contribute to the pool of P available for root uptake by macrophytes.

Refilling of Big Muskego Lake and associated vegetative regrowth were accompanied by high mean daily pH throughout the summer, presumably due to macrophyte photosynthesis. Although elevated pH can enhance rates of P release from sediment via ligand exchange (Drake and Heaney 1987; James, Barko, and Field 1996), this mechanism did not appear to be important for sediments exposed to high pH in Big Muskego Lake. In general, rates of P release measured in the laboratory did not increase significantly as a function of pH. However, rates of P release from sediments at pH values exceeding 9.3 units could not be reliably determined in laboratory systems using, for instance, NaOH additions to increase pH. Boers (1991) demonstrated that NaOH additions to sediment-water incubation systems for purposes of elevating pH (versus stripping CO₂ from the water column) resulted in artificially enhanced rates of P release from systems due to increases in alkalinity of the sediment pore water.

Results suggested that drawdown of Big Muskego Lake had both positive and negative impacts on sediment characteristics. Sediment dewatering was accompanied by marked increases in pore water P and rates of P release from the sediment, which can have a negative impact on water quality by

¹ Personal Communication, 2000, J. D. Madsen, Minnesota State University, Mankato, MN.

stimulating algal growth. Conversely, drawdown resulted in consolidation of sediment and a decline in organic matter content, which can have a positive impact on macrophyte growth potential. Positive and negative impacts of sediment desiccation on macrophyte and phytoplankton growth need to be evaluated when implementing lake drawdown and refill as a restoration technique for shallow lakes.

ACKNOWLEDGMENTS: We gratefully acknowledge Elly Best, Jürg Bloesch, John Madsen, and an anonymous reviewer for very fruitful improvements to this manuscript; Susan Fox and Kimberly Deevers of the Environmental Laboratory, U.S. Army Engineer Research and Development Center for sediment chemical analyses; and Dale Dressel, Michele Huppert, Valerie Hurtgen, Eugene Isherwood, Sara Krause, Brenda Lamb, Suzanne Riddick, and Holly Wallace of the U.S. Army Engineer Eau Galle Aquatic Ecology Laboratory for field sampling and chemical analyses. Funding was provided by the Wisconsin Department of Natural Resources and by the U.S. Army Engineer District, Detroit.

POINTS OF CONTACT: This technical note was written by Mr. William F. James and Mr. Harry L. Eakin of the Eau Galle Aquatic Ecology Laboratory, Environmental Laboratory (EL), U.S. Army Engineer Research and Development Center (ERDC), and Dr. John W. Barko, EL, ERDC. For additional information, contact the managers of the Aquatic Plant Control Research Program, Dr. Barko (601-634-3654, John.W.Barko@erdc.usace.army.mil), or Mr. Robert C. Gunkel, Jr. (601-634-3722, Robert.C.Gunkel@erdc.usace.army.mil). This technical note should be cited as follows:

James, W. F., Eakin, H. L., and Barko, J. W. (2001). "Rehabilitation of a shallow lake (Big Muskego Lake, Wisconsin) via drawdown: Sediment response," APCRP Technical Notes Collection (Aquatic Plant Control Technical Note PD-12), U.S. Army Engineer Research and Development Center, Vicksburg, MS. www.wes.army.mil/el/aqua.

REFERENCES:

- Allen, S. E., Grimshaw, H. M., Parkinson, J. A., and Quarmby, C. (1974). *Chemical analysis of ecological materials*. 1st ed., Blackwell Scientific Publications, Oxford.
- American Public Health Association. (1992). *Standard methods for the examination of water and wastewater*. 18th ed., Washington, DC.
- Barko, J. W., and Smart, R. M. (1986). "Sediment-related mechanisms of growth limitation in submersed macrophytes," *Ecology* 67, 1328-1340.
- Barko, J. W., Smart, R. M., Mcfarland, D. G., and Chen, R. L. (1988). "Interrelationships between the growth of *Hydrilla verticillata* (L.f.) Royle and sediment nutrient availability," *Aquat. Bot.* 32, 205-216.
- Boers, P. C. M. (1991). "The influence of pH on phosphate release from lake sediments," *Wat. Res.* 25, 309-311.
- Carlson, R. E. (1977). "A trophic state index for lakes," *Limnol. Oceanogr.* 22, 361-369.
- De Groot, C. J., and Van Wijck, C. (1993a). "The impact of desiccation of a freshwater marsh (Garcines Nord, Camargue, France) on sediment-water vegetation interactions; Part 1: The sediment chemistry," *Hydrobiologia* 252, 83-94.
- De Groot, C. J., and Van Wijck, C. (1993b). "The impact of desiccation of a freshwater marsh (Garcines Nord, Camargue, France) on sediment-water vegetation interactions; Part 3: The fractional composition and the phosphate adsorption characteristics of the sediment," *Hydrobiologia* 252, 105-116.

- Drake, J. C., and Heaney, S. I. (1987). "Occurrence of phosphorus and its potential remobilization in the littoral sediments of a productive English lake," *Freshwat. Biol.* 17, 513-523.
- Fabre, A. (1988). "Experimental studies on some factors influencing phosphorus solubilization in connection with the drawdown of a reservoir," *Hydrobiologia* 159, 153-158.
- Fabre, A. (1992). "Inorganic phosphate in exposed sediments of the River Garonne," *Hydrobiologia* 228, 37-42.
- Hieltjes, A., and Lijklema, L. (1980). "Fractionation of inorganic phosphates in calcareous sediment," *J. Environ. Qual.* 9, 405-407.
- James, W. F., and Barko, J. W. (1991). "Littoral-pelagic phosphorus dynamics during nighttime convective circulation," *Limnol. Oceanogr.* 36, 949-960.
- James, W. F., Barko, J. W., and Eakin, H. L. (1995). "Internal phosphorus loading in Lake Pepin, Upper Mississippi River," *J. Freshwat. Ecol.* 3, 269-276.
- James, W. F., Barko, J. W., and Field, S. J. (1996). "Phosphorus mobilization from littoral sediments of an inlet region in Lake Delavan, Wisconsin," *Arch. Hydrobiol.* 138, 245-257.
- Mehta, A. J., Parchure, T. M., Dixit, J. G., and Ariathuri, R. (1982). "Resuspension potential of deposited cohesive beds," *Estuarine Comparisons*. V. S. Kennedy, ed., Academic Press, NY, 591-609.
- Plumb, R. H. (1981). "Procedures for handling and chemical analysis of sediment and water samples," Technical Report EPA/CE-81-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Scheffer, M. (1998). *Ecology of shallow lakes*. Chapman and Hall, London.
- Scheffer, M. (1990). "Multiplicity of stable states in freshwater systems," *Hydrobiol.* 200/201, 475-486.
- Scheffer, M., Hosper, S. H., Meijer, M.-L., Moss, B., and Jeppesen, E. (1993). "Alternative equilibria in shallow lakes," *Trends Ecol. Evol.* 8, 275-279.
- Scheffer, M., Van Der Berg, M., Breukelaar, A., Breukers, C., Coops, H., Doef, R., and Meijer, M.-L. (1994). "Vegetated areas with clear water in turbid shallow lake," *Aquat. Bot.* 49, 193-196.
- Statistical Analysis System. (1994). "SAS/STAT Users Guide, Version 6, Fourth Edition," SAS Institute, Cary, NC.

NOTE: The contents of this technical note are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such products.